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DEVELOPMENT OF SCALING CRITERIA FOR TERRESTRIAL MICROCOSMS

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ABSTRACT

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Theoretical developments based on heat and moisture transfer in soil lead to dimensionless numbers that describe important processes taking place in a terrestrial microcosm. These numbers provide preliminary scientific criteria for scaling the results from microcosms both as a means of comparing two generally similar but non-identical systems as well as for better understanding the real world.

1. INTRODUCTION

The Toxic Substances Control Act requires the Environmental Protection Agency to develop rapid, reliable, and economical screening techniques to determine the ecological effects of chemical substances and mixtures and test for their carcinogenic, mutagenic and teratogenic effects.

The screening tests are designed to detect potentially harmful chemicals, as evidenced by their effects on test species and by their transformation, transport and bioaccumulation through food chains within a microcosm ecosystem. The determining test of whether or not a chemical actually produces harmful effects in the natural ecosystem may be more complex following a screening test. Even for these more elaborate tests laboratory ecosystems must prove more controllable, rapid, effective and economical than the alternative of real-world research.

According to an extensive theoretical analysis of microcosm design by Warren and Liss (1977), laboratory ecosystems at best represent capacities of low-level or only parts of more complex natural ecosystems. If capacities for persistence and production are decreased by the toxicant action on the microcosm system, according to these authors, it can be expected that the low-level natural ecosystem will experience similar alterations.

Warren and Liss maintain that the life history characteristics of candidate species within a microcosm determine the capacities of a laboratory ecosystem and that performances of the system are determined by its capacity and the conditions in its environment. They also maintain that multi-species systems must persist for several generations in order to achieve any semblance of a natural system.

Warren and Liss stress the need for classification schemes to aid in microcosm design and in generalization of the observational data. For example, taxonomic classification of species reflects evolutionary similarities and differences. So does classification with respect to trophic level which groups the species into similar sets of herbivores, omnivores, decomposers, etc. Another classification groups the organismic objects according to their inter-relationships such as predation, competition, etc. The classification of the physical environment and the classification of the toxicants according to their structure, behavior, etc., are also discussed by the authors.

When comparing two systems, the classification of the biotic component helps determine similar groups of organisms. For comparison of the physical component, Warren and Liss refer to the work of Fry (1947), who grouped the physical environmental objects into similar operational classes, for example, lethal, controlling, limiting, stressing, etc. This mode of classifying the physical environment is defined not in terms of physical components and processes, but indirectly by the effects the components produce on the organisms within the microcosm. The identification of various physical components and processes with such effects must be an outcome of any microcosm study. We must endeavor to develop a classification system of the physical environment that is direct, definable in terms of physical components and processes, and measurable with known instrumental precision. This is an important design

requirement needed for better defining the operational rules of Fry's classification.

The physical components and processes in a multi-species terrestrial microcosm are made up of very complex mixes. The rates of air circulation, leachate removal and water supply, the intensity and duration of radiant energy supply, and the level of the ambient temperature in the laboratory all can be manipulated to maintain controlled temperature and moisture levels in the soil matrix and the ambient air of the microcosm environment. The physical environment of the microcosm together with the soil type and the spacial dimensions of the system determine to a large extent the growth and behavior of vegetation and other living organisms confined within it. In this manner of evaluation, the operational physical environment of Fry is linked firmly with the physical processes and components that govern their maintenance.

The application of toxicants to a microcosm may influence the growth and behavior of its components. The study of such responses of the biotic components, the analysis of the distribution, bioaccumulation, transport and transformation within the entire microcosm system play determining roles in the outcome of toxicant screening.

Toxicants may be tested at varying dose levels applied to separate microcosms. The results from several such systems must be compared among themselves as well as with a control containing no toxicant. It is with respect to the proper interpretation and comparison of results from these systems that the question of similarity of system components and processes arises. The same question also arises when toxicants are screened at different laboratories by different researchers where it might be necessary to deviate slightly from certain prescribed requirements in order to more clearly match a given facility, operation or hypothesis (Gillett and Witt 1977).

The ability to directly measure the physical environment of a microcosm and the ability to group them in similar sets of conditions is particularly significant if we intend to use microcosm systems extensively for toxicant screening. In this paper we will be concerned mainly with the physical processes and components that enter the design of a terrestrial type microcosm.

For the grouping in similar sets of microcosm systems, we draw heavily from the general principle of similarity theory commonly applied to the design and understanding of physical systems.

2. GENERAL APPROACH AND EXAMPLES

2.1 UNCOUPLED ABIOTIC PROCESSES

Consider a column of soil in a lysimeter that is devoid of plants and living organisms and is dried to a state of equilibrium with the water potential of the air. Exchange of energy in this case must account for the fact that soil moisture varies with variation of water conditions of the air medium. Moreover, with variation of temperature a certain amount of gas will be evolved or absorbed in a reversible manner. Transfer of energy and mass will be balanced during a 24-hour day and tne mean amount of heat and mass of the soil will remain constant (Nichiporovich, 1975).

If the soil is inhabited by microorganisms and contains sufficient organic substances, heat will evolve from the microorganisms during their life activity and the decomposition of organic compounds. However, this contribution to the soil heat balance is generally negligible. Many chemical transformations of substances in the soil may occur and mass exchange with the environment should now include evolution of carbon dioxide and absorption of oxygen. In some cases uptake of nitrogen and release of other gases may be involved. Thus both energy and mass exchanges take place due to the presence of microorganisms.

The presence of plants will alter the picture further. Green plants affect the energy and mass transfer processes in a complex manner: carbon from atmospheric CO_2 and water and mineral nutrients from the soil are rapidly incorporated into the photosynthetic organs. These elements, and hydrogen from photochemically decomposed water, combine to form organic molecules under the action of sunlight; simultaneously oxygen is liberated into the atmosphere. This shows that "plant-cover soil system" photosynthesis proceeds with an active balance. Its total mass increases, as does the amount of bound energy.

The situation is further complicated as grazing insects and other animals are added to the system. In a microcosm environment introduction of toxicants adds yet a new dimension. We will now be dealing with behavioral problems as well as animal life activities such as "tunneling" and constant "working" of the soil. Outside the soil environment, plant life interacts with wind motion damping its turbulence, depleting its CO_2, etc.

It must be obvious that development of complete scaling rules for a microcosm containing interactive physical, chemical and behavioral factors is an impossible task. We must follow the suggestion made by Haefner and Gillett (1976) that the biotic and the abiotic systems are more or less "uncoupled", at least in the first order of approximation. For example, the energy imbalance of photosynthesis is about 2-5% of incident radiation. This amount can either be ignored or included as a "sink" without disrupting the major processes of heat transfer. Also, the net exchange of CO_2, O_2, N_2, etc., with air can be approximately accounted for if the total mass of air is not appreciably changed in the process. The impact of active root systems, tunneling, etc., can be included as a part of the physical character of the soil, affecting heat and mass transfer.

In other words, the rules for uncoupled systems can be developed in a formal theoretical manner, but the utility of their application is confirmed or denied by the evidence of carefully conducted experiments, either existing or planned (Gillett and Witt 1978).

Again, as a general guideline, an attempt will be made to account for those biotic processes that tend to significantly alter mass, momentum and energy transfer in the microcosm. In this manner, even though we would not fully understand th completely coupled system, we would increase the probability of successfully simulating a system, uncoupled, but reasonably realistic.

2.2 FUNDAMENTALS OF THE THEORY OF SIMILARITY

The concept and the formal statement of the general Theory of Similarity is somewhat abstract, but it has a far-reaching practical application in the

conduct of scientific experiments and in interpretation and presentation of data. One statement of this theory is "Two phenomena are similar if they are described by one and the same system of differential equations and have similar conditions of single-valuedness" (Luikov, 1966). In relation to the problems of microcosms, the system of differnetial equations referred to in the theorem is derived from the application of conservation of mass, momentum and energy. The conditions of unambiguity or single-valuedness are (a) geometrical properties of the system, such as shape and spacial dimensions of the box, the depth of the soil, etc., (b) all physical constants of the bodies which are essential for the phenomena under consideration, e.g., soil density and texture, the diffusivity for heat and moisture, etc; (c) initial conditions describing the state of the system at the initial instant, and (d) conditions of interaction of the system with the surrounding medium, e.g., the initial moisture content of air and soil, their transportation, boundary conditions, (for example, the exchange of heat by conduction and radiation, the exchange of moisture and heat by air recirculation) and water addition and removal, etc.

The system of differential equations describes a whole class of phenomena. In order to solve a single problem relating to a microcosm at hand, we can follow one of two paths. (1) Obtain a universal solution of the system of equations and use numerical values of single-valuedness conditions to solve a single problem. This is the most direct, but also the most difficult and at times, an impossible approach. (2) We may use the general Theory of Similarity to define a special concept of a group of phenomena, a concept that is narrower than a whole class but much broader than a concept of a single phenomena. The group is formed by an appropriate restriction of the class concept through assignment of the conditions of single-valuedness. The difficulty is that we cannot always achieve this grouping, but when we do, we can immediately overcome the deficiency of purely empirical procedures -- that is the difficulty of extending results obtained from a given experiment to other phenomena different from that studied. In this indirect approach, combinations of experimental and theoretical procedures become possible without actually having to solve the system of differential equations.

By appropriately transforming the equations and their conditions of single-valuedness, we arrive at criteria that bound the group of phenomena together. The individual phenomena in this group differ from one another by a set of multipliers, or dimensionless numbers. It is only in this manner that we can extend the results from a single experiment to a wider group of phenomena.

2.3 DIMENSIONLESS NUMBERS AS SCALING CRITERIA

To demonstrate the essential role of the Theory of Similarity, we provide two examples (Luikov 1966), each using a multiplier that trnasforms results from a class of processes or phenomena to a group of processes or phenomena.

Example 1

Examine the process of constructing a group of geometric figures as in Figure 1a. We can assume that the rectangles belong to a whole class of plane shapes with the common property of all angles being right angles. To distinguish one single rectangle from the class, the numerical values of the sides ℓ_1 and ℓ_2 must be given: In this case ℓ_1 and ℓ_2 are the conditions of single-valuedness. But a distinct group of figures will be obtained if we assume the ratio of sides are a constant equal to the coefficient K_ℓ. By attaching different values to the coefficient, a whole series of figures is obtained (Fig. 1b). These figures are similar among themselves because their sides are proportional, i.e.

$$\frac{\ell_1'}{\ell_2'} = \frac{\ell_1''}{\ell_2''} = \frac{\ell_1'''}{\ell_2'''} = K_\ell \qquad (1)$$

An individual rectangle of this group can be identified in detail, for example, by actual measurement of its sides, after which the properties of the entire group becomes known. This is one example of an extension of a single experiment to a group of similar processes.

Sometimes it is difficult to maintain exact geometric similarity. For example, if the depth of the soil is transformed by a factor K_ℓ, all linear

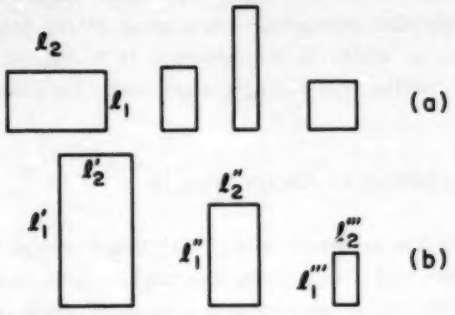

Figure 1. Class and group of plane rectangular figures: a) class of figures (sides have arbitrary length and b) group of similar figures (the ratio of sides is constant).

Dimensions such as soil grain size must also be similarly transformed, otherwise the transformation is distorted. The formal Theory of Similarity does not deal with the problem of distortion, even though distorted models are widely used (Bogardi 1974). In these cases it is endeavored to ensure the similarity of the dominating processes and phenomena.

Example 2

Consider the partial differential equation:

$$a \frac{\partial^2 t}{\partial x^2} = \frac{\partial t}{\partial \tau} \qquad (2)$$

which is generally referred to as the one-dimensional diffusion equation. Depending on the physical significance attached to the variables, equation (2) is representative of a wide class of physical phenomena. For example, if we define t as temperature, a as thermal diffusivity, τ as time and choose x as a

coordinate directed away from an infinite plane, equation (2) describes the propagation of heat in an infinite solid, or soil when the soil is suddenly heated to a temperature exceeding that of the surroundings. Again, we might define t as a velocity of a flow parallel to a plate, choose a as kinematic viscosity, let x be the normal distance from the plate and τ be time. Equation (2) then describes the velocity variation of the flow if the wall is suddenly set into motion. Diffusion of vorticity in a fluid, slowing down of neutrons in matter, etc., are also represented by equation 2. Each of these is a <u>class</u> of processes.

The conditions of single-valuedness can be stated in a general way, for example for a class of heat transfer problems, but for convenience we assume zero temperature gradient at the surface and zero initial conditions. Then, assume we have two systems describing heat transfer into soil. One is defined by the value of its parameters t', τ', x' and a' and the other by $t''=K_t t'$, $\tau''=K_\tau \tau'$, $x''=K_x x'$, and $a''=K_a a'$. The second system is derived from the first one by corresponding transformation multipliers. To establish similarity for these two systems equation 2 must remain valid on transformation from the first to the second system. Hence:

$$a' \frac{\partial^2 t'}{\partial x'^2} = \frac{\partial t'}{\partial \tau'} \tag{3}$$

$$a'' \frac{\partial^2 t''}{\partial x''^2} = \frac{\partial t''}{\partial \tau''} \tag{4}$$

By expressing the prime quantities in terms of double prime quantities, we obtain:

$$\frac{K_t K_a}{K_x^2} \left(a' \frac{\partial^2 t'}{\partial x'^2}\right) = \frac{K_t}{K_\tau} \left(\frac{\partial t'}{\partial \tau'}\right) \tag{5}$$

By comparing equation (5) with (3), it is seen that they can be simultaneously true only if:

$$\frac{K_t K_a}{K_x^2} = \frac{K_t}{K_\tau} \quad \text{or} \quad \frac{K_a K_\tau}{K_x^2} = 1 \tag{6}$$

When we insert the physical values for the multipliers in equation (6), we obtain the dimensionless number: $a'\tau'/\ell'^2 = a''\tau''/\ell''^2$ or simply,

$$Fo = \frac{a\tau}{\ell^2} \tag{7}$$

This is commonly known as the Fourier (Fo) number. Its magnitude is a measure of the degree that heating or cooling effects have penetrated through the solid (or soil). If a/ℓ^2 is small, a large τ value is required before significant temperature changes occur through the solid, if a/ℓ^2 is large, the reverse is true.

2.4 GENERALIZATION OF EXPERIMENTAL DATA

Note that the role played by the dimensionless numbers in the preceding examples is to group all rectangles (Example 1) and all systems of heat conduction (Example 2). The grouping is accomplished by the dimensionless numbers K_ℓ and Fo respectively. Within each of the two groups of phenomena the individual members differ by only a scale factor; that is, all processes within each group are "similar".

For the case of Example 2, one can state the problem of similarity in a converse manner; namely, if the temperature distribution in two geometrically similar bodies is the same, then Fo for these processes must also be equal, regardless of the individual values a, τ and ℓ. The dimensionless combination is a generalized variable or criterion of similarity. One can regard the Fourier number as the generalized time, transforming one process into a similar process.

Instead of computing the values of all like points of two similar systems, it is sufficient to compare dimensionless numbers that contain the mean values of the quantities in the range under consideration. This is fundamental in considering experimental data. In an experiment related to Example 2, it is necessary to measure all the values which are parts of the dimensionless criterion Fo. However, the results of the experiment must be pre-

sented not in terms of a relationship between separate values of a, τ, ℓ, t and x, but in terms of temperature as a function of the Fourier number and a coordinate system $\frac{x}{\ell}$, i.e.,

$$t = f(\frac{x}{\ell}, Fo) \qquad (8)$$

The functional form of equation (8) can be determined from experimental data. Once this is done, the group representation will be narrowed down to a single or some specified experiments.

This example demonstrates the power of Theory of Similarity and dimensional reasoning. In more complex systems with tens of variables the number of dimensionless criteria increases. Treating experimental data with dimensionless criteria permits a rational design of experiments and a condensed presentation of results.

3. SPECIFIC APPROACH

3.1 MAJOR PROCESSES OF HEAT AND MASS TRANSFER IN TERRESTRIAL SYSTEMS

To introduce the criteria for scaling the processes of heat and mass transfer in a real soil environment, let us explore the nature of these processes and identify some key physical parameters of (a) the soil, (b) liquid water transport, (c) vapor transport, (d) heat transport, and (e) boundary conditions.

(a) Soil may be classified as clay, silt, fine and coarse sand, or gravel according to average grain size $\bar{d}$. The values of $\bar{d}$ distinguishing the four soil types are .002, 0.02, 0.2 and 2 mm. Each soil type has a distribution of particle sizes around the mean. Detailed knowledge of this distribution and the packing arrangement of particles leads to pore size distribution in the soil, which one can estimate by ε, a dimensionless parameter. The quantity $1/\varepsilon$ represents resistance to diffusion of vapor inside the soil. It shows how many times the coefficient of vapor diffusion in air, a_v, is greater than the coefficient of vapor diffusion within the body of the soil. In a similar

manner, the resistance of heat diffusion in the solid parts of the soil must be obtained. These coefficients change dramatically with the moisture content. Therefore, for each soil type, they must be determined experimentally for several moisture contents.

The soil is saturated when water completely fills the space between the particles. When unsaturated, parts of the space contain air and water vapor. Under all conditions except at very high moisture content the air is in a continuum phase. When the continuity is interrupted, air exists in the form of bubbles distributed throughout the continuous liquid phase.

(b) To consider liquid flow within the soil, one must be satisfied with a continuous approach which disregards the particulate structure. The liquid mass transport is thus readily linked with the gradient of the capillary liquid potential. The coefficient that links the liquid potential with the soil property ε and mass flow is the diffusity coefficient a_ℓ. This is a function of moisture content because the cross sectional area available for the flow of the liquid changes with ε. One also must expect a rapid change in the moislture diffusivity as the liquid changes from a discrete to continuous phase.

(c) Both vapor and mass transport may take place under isothermal conditions primarily by diffusion. The vapor mass transport under temperature gradient may contain convection, because the air in the soil may no longer be at rest. The coefficient of vapor diffusion a_v relates the non-convective vapor mass transport in the soil with the soil properties and the gradient of capillary vapor potential. The moisture diffusivity a_m of vapor and liquid can be used to account for both phases when they occur simultaneously. The moisture diffusivity a_m depends on soil types, temperature, and pressure.

(d) Energy transport in the soil will occur by heat conduction in the solid and liquid (heat conduction in the air can be neglected) and by transport of the heat of evaporation r. When the air in the soil is moving, energy also will be transported by convection. The coefficient of thermal diffusivity a_q connects the heat flux to the soil properties and the gradient of

temperature in the soil. Among the soil properties of importance are soil heat capacity c_q, and bulk density.

For temperatures as they generally occur (in the shade), the convective transport within the body of the soil contributes to the total heat flux in a minor way. However, the contribution increases rapidly with increasing temperature, so that around 60°C (when the soil is saturated) the convective contribution could equal the contribution from conduction (Eckert and Pfender 1978).

(e) Energy and mass transfers must be considered for the soil column extending from the top of the vegetation to the soil depth where vertical transfer of energy and mass is negligible. For the daily cycle of input solar radiation, the depth for heat transfer averages from 50 to 100 cm, (Kreith and Sellers 1975). For the moisture, it extends to the impervious layer of the soil where groundwater flows horizontally.

(f) The net radiation, which is the difference between the incoming and outgoing streams of solar and longwave sky or terrestrial radiation, must be balanced by (1) the sensible heat flux between the surface and air, (2) the evaporative heat flux between the surface and the air, and (3) the total heat flux between the surface and the soil column itself. The net radiation is a function of incoming solar radiation, surface reflectivity, surface emissivity, surface temperature, air temperature and vapor pressure.

(g) The sensible heat flux is directly proportional to the temperature difference between the surface and air. The important quantity entering the proportionality is the coefficient of surface heat transfer α_q. It varies strongly with turbulence of the ambient air. The evaporative flux likewise introduces into the problem a mass transfer coefficient denoted by α_m. It relates the flux with vapor pressure of the soil and air.

The preceding discussion is a very brief account of heat and mass transfer processes that take place in abiotic systems of soil environment. These are uncoupled from biotic processes only in the sense that major impacts of

plant and animal activities must be combined and included in an appropriate way into one or more of the parameters outlined above. Boundary conditions have been taken at the air-soil surface and no complications caused by "edge effects" etc., that are common in microcosms are considered. The following sections include a more specific account of the rules and criteria that scale these processes from one system into another.

3.2 PROPOSED CRITERIA FOR SCALING MICROCOSM PROCESSES

The complete boundary conditions suitable for a microcosm environment have not been analyzed as a part of the processes of heat and mass transfer. Notwithstanding, we propose to begin with an analysis that otherwise most closely approximates microcisms and use this scaling criterion as a preliminary step. Appropriate modifications must be introduced only as opportunities for further progress become evident.

Luikov (1966) in his celebrated book, and more recently in a review paper (1975) derived the systems of differential equations of heat and mass transfer in capillary porous media. He then presented a comprehensive solution for an infinite plate with impermeable bottom layer and an exposed top. We shall make extensive use of his analysis without recounting the mathematics, which is somewhat detailed and involved.

The criteria for scaling heat and mass transfer are dimensionless numbers that transform space and time distribution of temperature t^* and moisture θ^* from one system into another. Both t^* and θ^* are nondimensionalized with respect to the initial states of temperature and moisture differences, respectively, in the soil and the air. These functions, expressed implicitly in terms of scaling criteria are:

$$t^* = f\ \left(\frac{x}{R}, Fo, Lu, Bi_q, Bi_m, \varepsilon, Ko, Pn\right)$$

$$\theta^* = g\ \left(\frac{x}{R}, Fo, Lu, Bi_q, Bi_m, \varepsilon, Ko, Pn\right)$$

We shall give the physical meaning of these criteria and rely on the reader's intuition by recalling the previous two sections on similarity anal-

ysis to establish general acceptability of the following statements. It will suffice to note from example 2 given earlier that t^* can be written as a function of $\frac{x}{R}$ and Fo, where x is the distance in the soil, R total depth of the soil and Fo the Fourier number. We recall that the simplicity of this result stems from the fact that the soil was considered completely dry, homogenous, and there was no mass transfer whatsoever. With respect to the proposed, more complex system, we will, of course, use additional criteria. It will help if the reader establishes a mental picture of relations betwen the criteria, the processes they each represent, and the processes they each interact with.

Criterion $\frac{x}{R}$

This is the dimensionless space coordinate. It is normalized with respect to the depth of the soil R. It does not matter what the absolute value of x might be, nor in what units it is presented, it is only necessary to know the relative depth expressed in terms of a fraction of the total depth in the two systems being compared. In this problem $\frac{x}{R}$ is the only coordinate system. It means that θ^* and t^* are invariant with other dimensions. It means there is no edge effect or major non-homogeneity in the soil, in either the horizontal or the lateral directions. With respect to a confined system such as a microcosm, it means that attention must be focused to those central points of the microcosm that are immune to wall effects. Otherwise, the problem must be reworked completely to comply with the principle of single-valuedness discussed earlier.

Criterion Fo

This is the familiar Fourier number. This parameter translates the time scale from one system to another. Numerically, it is equal to $a_q\tau/R^2$, that is, a measure of thermal diffusivity, a_q with time τ as heat moves across a unit cross section of the soil.

Criterion Lu

This is simply the ratio of mass diffusivity for moisture to thermal diffusivity for heat, i.e., a_m/a_q. In the transformation from one system to another, if we choose to associate thermal diffusivity with the time coordinate as we have done by choosing the Fourier number, the connection of mass transfer with the time coordinate will be established by knowing Lu for the two systems. An appropriate form of Lu may also be used to account for filtration, i.e., $Lu_p = a_p/a_q$ where a_p is filtration diffusivity. Lu increases with moisture content of a system. Thus, when the spread of mass transfer potential is greater than temperature, Lu>1. For this reason, the filtration number Lu_p could be 10 to 100 times greater than Lu.

Criterion Bi

This is commonly known as the Biot Number. It relates the heat and mass transfer between the soil and air. Its numerical value is $\alpha_q R/a_q$ for Bi_q and $\alpha_m R/a_m$ for Bi_m. As we know from the earlier discussion α_q and α_m are the convective transfer coefficients for heat and for moisture, respectively. Again, the connection between time coordinates of the system and transfer of heat (mass) from and to the soil is established by Criterion Bi. In a like manner Bi_r can be defined for radiative transport which includes surface reflectivity and emissivity.

Criterion ε

Is a number between zero and one. It is zero when mass transfer takes place by means of liquid transfer alone. It is one when mass transfer takes place by evaporation alone. Any value between zero and one implies combined processes of liquid transport with evaporation.

Criterion Ko

This is the ratio of heat ($r\Delta u$) expended in evaporation of incremental mass Δu of liquid water in heating the wet soil to an equivalent amount

($c_q \Delta t$). This is one way of bringing the specific heat of the soil c_q and the heat of evaporation r into account for the transformation.

Criterion Pn

As explained earlier, mass transfer in either vapor or liquid phase can take place within the soil as a direct consequence of temperature gradient. Pn links this interaction. As mass is transferred from one point to another under its own gradient, its potential drops. Pn expresses this drop in terms of incremental mass transfer Δu and temperature drop Δt. Thus, $pn = \frac{\delta \Delta \tau}{\Delta u}$, where δ is a constant of thermal gradient coefficient. Just as in the case of Ko, Pn is used to bring another thermodynamic property, δ, into account.

Since ε, c_p, r and δ represent mechanical and thermodynamic properties, a generalized criterion containing all these properties is often encountered in analysis. It is $Fe = \frac{\varepsilon \delta r}{cq}$, also obtained from the product of the last 3 criteria, i.e., $Fe = \varepsilon KoPn$. This number is independent of the heat and mass transfer potentials.

4. DISCUSSION

The foregoing presentation demonstrates the concept of transferability from one system to another by using analytically-derived transformations based on similarity criteria. According to these criteria, two systems are similar only if the corresponding criteria governing those processes are numerically equal.

An example will demonstrate this conclusion. Consider Figure 2 reproduced from Luikov (1966, p. 299). In this figure, Luikov plots the rates of change of t^* and θ^* with respect to Fourier number for several Lu numbers. Since, according to the previous discussion, the Fourier number is essentially the time coordinate for the process, these figures actually depict the time rate of change of moisture potential and temperature at a given point in the system.

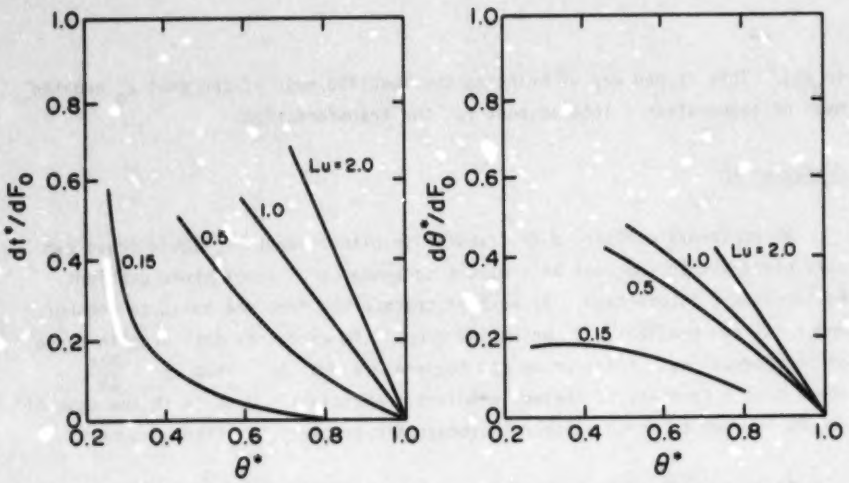

FIGURE 2. Connection Between Heat-Mass Transfer Potentials and Their Rates of Change With Lu.

Suppose now that we have two systems, I and II, for which $Fo_I = Fo_{II}$ but $Lu_I = 0.5$ and $Lu_{II} = 0.15$. This is entirely possible, since all we need to do is to choose the soil properties (say, by controlled moisture, compaction, etc.) in system I, so that its diffusivity a_m differs by a factor of 0.5/0.15 = 3.3 from system II. For example, quartz sand at moisture contents of 2% and 16% has the same thermal diffusivity, a_q equal approximately to 20 x 10^{-4} m^2/hr but has moisture diffusivity a_m = 4.8 x 10^{-4} m^2/hr and 16 x 10^{-4} m^2/hr respectively.

With these inputs we use Figure 2 to calculate the appropriate rates in the two systems at a point where $\theta^* = 0.6$. The latter choice is entirely arbitrary. We find from these theoretical calculations that the rate of temperature change differs by a factor of 8.6 and moisture by a factor of 2.5, respectively, between systems I and II.

This is a dramatic change in time rate of important abiotic processes caused by an apparently innocent variation of one soil property. The analysis can be used to evaluate the relative importance of other system properties, since they are not all equally important.

5. CONCLUSIONS AND RECOMMENDATIONS

It was demonstrated in this paper first by discussion of fundamentals of Theory of Similarity, second by physical reasoning, third by theoretical analysis of specific problems and finally by a specific typical example, that two apparently similar microcosm systems could produce totally divergent results, for example with respect to mass and heat transfer.

These differences were calculated for the abiotic processes. We do not know the extent or exact nature of all impacts of these differences on biotic processes. Undoubtedly, the impact of these differences on the chemodynamics of toxic substances in the abiotic portion would be to change chemical concentration of the toxicant with respect to space and time. To the extent that biological response is controlled by concentration of toxicants, the system will differ more or less markedly in response to exposure to toxicants. The accuracy, sensitivity and even practicability of measurements (and consequent extrapolation to the real world) of toxic substances impact therefore depend on sound and uniform similarity criteria applied to individual test systems.

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